

7 VISUAL FUNCTION

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In order to design a helmet-mounted display (HMD) that most effectively couples with the eye and optimizes visual performance, the designer should have a basic understanding of the capabilities and performance of the visual system. This includes an understanding of the following:

- The physical nature of light
- How the eye forms an image
- Refractive errors and their correction
- Spatial vision, including visual acuity and contrast sensitivity
- Peripheral vision
- Adaptation to high and low illumination
- Color vision
- Accommodation
- The eye's temporal responsiveness
- Eye movements
- Binocular vision

The Physical Nature of Light

While vision is predominately a physiological process, it is all made possible by that part of the electromagnetic (EM) spectrum we call light. We see the world around us and the objects in it because of light energy that is either emitted by or reflected off of these objects. An elementary understanding of light and its role in vision can be both instructive and useful.

The universe is filled with energy. The total span of this energy is represented by the EM spectrum (Figure 7-1). At any given place along the spectrum, the energy is characterized by a specific frequency (or wavelength). Frequency (f) is inversely proportional to wavelength (λ), as shown in Equation 7-1, where c is the speed of light.

$$f = \frac{c}{\lambda} \quad \text{Equation 7-1}$$

While continuous in nature, it is convenient to divide the spectrum into subdivisions. At one end of the spectrum is the highest frequency (shortest wavelength) subdivision known as the gamma rays (Figure 7-2). Gamma rays have frequencies to the order of 10^{20} Hertz (Hz) and higher, and wavelengths of 10^{-11} meters. These rays have the more energy than any other part of the EM spectrum. They are produced by atoms undergoing radioactive decay and by nuclear explosions. Gamma rays have practical applications in medicine and in industry. In medicine they are used to kill cancerous cells and sterilize medical equipment. In the food industry, they are used to kill bacteria and insects and to maintain freshness (Tauxe, 2003).

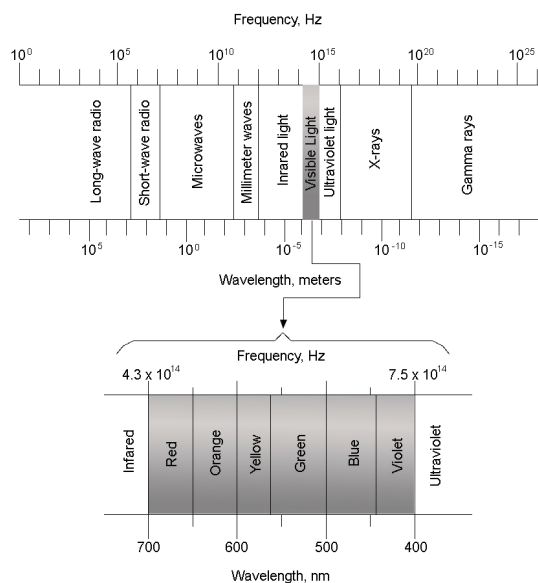


Figure 7-1. The electromagnetic spectrum.

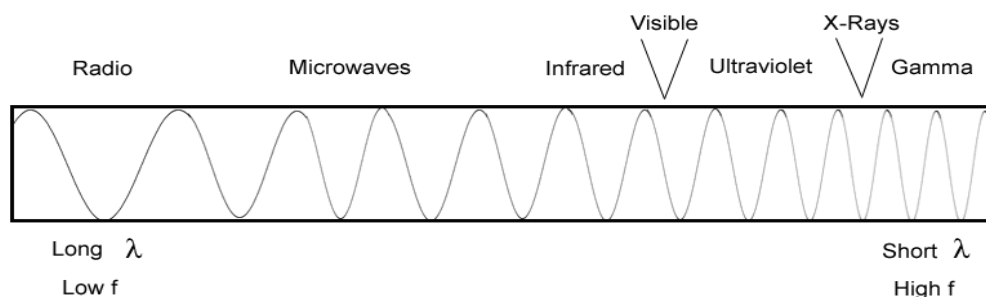


Figure 7-2. The electromagnetic spectrum as a range of frequencies and wavelengths.

At the other end of the spectrum are radio waves, having the lowest frequencies ($<10^6$ Hz) and longest wavelengths ($>10^2$ meters). The radio wave part of the spectrum is often further divided into short- and long-waves. This part of the spectrum is the least energetic. Uses of radio waves include AM and FM radio, television and cell phones.

For our purpose the most important part of the EM spectrum is visible light, i.e., that part of the spectrum that the human eye can detect or “see.” It is a very small part of the complete spectrum. When studying vision, it is customary to refer to the wavelength of a specific part of the visible light spectrum. There are no exact bounds to the visible spectrum. A typical human eye will respond to wavelengths from 400 to 700 nm, but this can vary from person to person. As will be explained later, during daylight the eye typically has its maximum sensitivity at around 555 nm, and in low illumination, the eye is optimized at approximately 510 nm.

Different wavelengths within the visible spectrum are associated with certain colors. That is, when we see light of a particular wavelength, we perceive a particular color. Sir Isaac Newton is credited with first showing that light shining through a prism will be separated into its different wavelengths and will thus show the various colors of visible light. This separation of visible light into its different colors is known as dispersion.

Newton divided the visible spectrum into seven named colors: Red, orange, yellow, green, blue, indigo, and violet, which are represented by the mnemonic “ROYGBIV.” For accuracy, “indigo” is not actually observed in the spectrum but is traditionally added to the list so that there is a vowel in Roy's last name. The red is associated

with the longer wavelengths and violet with the shorter wavelengths. Between red and violet, there is a continuous range of wavelengths and, hence, colors.

The last important principle of light (and the entire EM spectrum), for the purpose of this discussion, is known as particle-wave duality. It is generally accepted that light is composed of packets of energy called photons, which display some of the properties of waves and some of the properties of particles. The energy of an individual photon is proportional to its frequency; the higher the frequency (or shorter the wavelength), the greater the energy. The photon represents the smallest amount of light energy that can be produced. The human eye is remarkable in that under ideal conditions, a rod receptor in the retina at the back of the eye can respond to the energy of a single photon.

The particle nature of light explains the reflection of light rays and the photoelectric effect; the wave nature of light explains refraction, interference and polarization. Simply stated, light exhibits properties both of particles and of waves. For human vision and the following discussion of how the eye forms an image, the dual nature of light will be used in the sense that the path of light entering the eye will be treated as light rays associated with waves that obey the laws of reflection and refraction.

How the Eye Forms an Image

In a simplistic representation, vision can be separated into two mechanisms: one that encompasses the collection and focusing of light on the photoreceptors in the retina at the back of the eye and the one that consists of the physiological and cognitive processes that follow.

Consider the diagram in Figure 7-3. A simple object of interest, here represented as a tree, is depicted. As a luminous object, the tree can be seen only when light from a source such as the sun or moon falls upon the tree and is reflected. Light will be reflected from, and can be considered as originating from, every point on the tree. It is convenient to treat light originating from each point as rays that travel in straight lines.

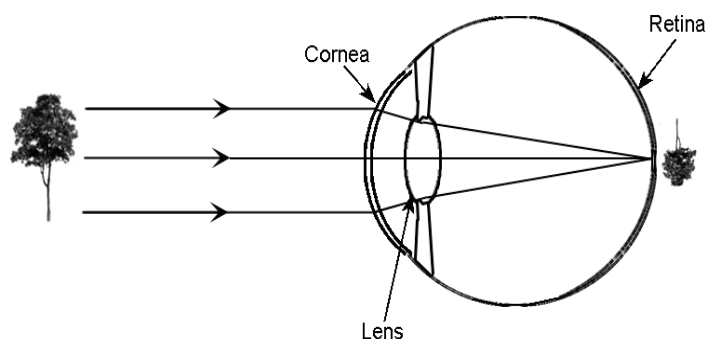


Figure 7-3. Formation of an image.

We need only to concern ourselves with those rays that enter the eye. Due to the nature of optics, we also need only consider a representative number of these rays in order to investigate the image formation process. In Figure 7-3, three rays have been depicted, one each from the many that originate from the top, middle and bottom of the tree.

In our basic model, the eye uses a simple lens system (cornea plus the lens) to form an image of the tree on the retina. In an often-used analogy, the eye is compared to an old-fashion analog camera (Figure 7-4). In this analogy, the retina acts as the film, the lenses of the eye acts as the lenses of the camera, and the iris acts as a diaphragm controlling the amount of light entering the eye-camera. Except for those entering along the optical

axis of the eye, the light rays are refracted (bent) by the lenses and focused onto the retina. As rays from all points of the tree are considered, a two-dimensional image of the tree, although inverted, is formed on the retina (Figure 7-3). The brain later turns this image “right way up” in the stages leading up to conscious perception.

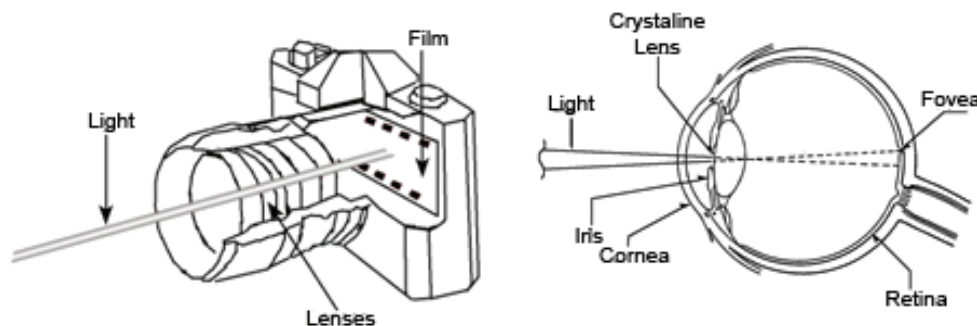


Figure 7-4. The camera-eye analogy.

Note that the eye's optical system includes two lenses, the *cornea*, at the front of the eye, and the lens, inside the eye. The cornea acts as a fixed-focus converging lens, providing about 65% of the focusing power of the eye; the internal lens acts as a variable focus lens. It is controlled by a set of muscles (the ciliary muscles) that relax and contract, thereby changing the lens' curvature and power. This mechanism provides the fine-focusing that allows the cornea-lens system to form a sharp image on the retina over a range of object distances (Atchison and Smith, 2000; Benjamin, 2006; Bennett and Rabbetts, 1991; Goss and West, 2002).

The cornea

The cornea is a thin, transparent tissue at the front of the eye consisting mostly of a collagen-based stromal layer that is about 0.5 mm thick. A thin tear film coats the anterior corneal surface, making it into a smooth high-quality optical surface. Wind, low humidity, high altitude, certain diseases, drugs or refractive surgery can affect the tear layer and lead to corneal surface drying, which causes irritation and transient blurred vision. The cornea is a living tissue and requires oxygen, absorbed directly from the atmosphere, in order to maintain normal metabolism and transparency. Hypoxia due to the environment or contact lens wear can lead to corneal swelling, optical distortion, and loss of transparency. Surface drying and hypoxia can be especially troublesome for pilots or aircrew who wear contact lenses, or who have had refractive surgery. The cornea's refractive power is determined largely by its anterior and posterior surface curvatures. One way to correct refractive errors of the eye is to alter the curvature or shape of the anterior corneal surface, as is done in refractive surgery (Bron, Tripathi and Tripath, 1997; Kaufman and Alm, 2003).

The lens

The internal lens, also called the crystalline lens or simply called the lens, has less than half the refractive power of the cornea, but it fulfills an important unique function. By adjusting its shape it allows the eye to accommodate, that is, focus for different viewing distances. Accommodation declines with age. By about age 45, most people have difficulty focusing at normal reading distances, and need help from bifocals or reading glasses. Opacities of the lens, known as cataracts, may be caused by trauma, disease, toxicity, exposure to radiation, or as a normal process of aging. Depending on the severity and distribution, they can degrade vision. If the visual impact is severe enough, the cataract can be surgically removed and replaced with an artificial intraocular lens (Benjamin, 2006; Goss and West, 2002).

The pupil

The pupil, the aperture at the center of the iris, controls the amount of light entering the eye by changing size in response to light. The pupil's diameter is usually close to 4 mm, but in dim illumination it can dilate to about 7 mm, and in bright illumination it constricts to about 2 mm. Retinal illumination, in trolands (E'), may be computed by the following formula, where object luminance (L) is expressed in candelas/m² and pupil area (A) is given in square mm (Schwartz, 2004).

$$E' = LA$$

Equation 7-2

Since pupil area changes with the square of its radius, retinal illumination also changes with the square of pupil radius. Pupil size varies somewhat from person to person, and with age, race, distance of the object being viewed, emotional state, fatigue and in response to certain drugs. Pupil size also affects retinal image quality. A small pupil increases the eye's depth of focus and minimizes the affect of small optical errors. For example, following LASIK (laser in-situ keratomileusis) refractive surgery, patients with small residual optical aberrations may see well during the day when illumination is high and the pupils are small. At night, however as the pupils naturally dilate, residual aberrations may degrade vision noticeably. Another example is an aviator aged 40-50, who may be able to read without bifocals in high illumination when the pupil is small, but who may have difficulty reading in low light.

The retina

The retina is an intricate tissue layer that contains 10 distinct sub-layers, over 100 million photoreceptor cells and complex neural networks that process the image. It is about 0.5 mm thick and lines the back half of the eyeball's interior, and so receives the extended image formed by the cornea and lens. If you examine the retina using an ophthalmoscope, it will appear as a red surface, due to its rich blood supply, with a prominent pale oval, on the nasal side, which is the optic nerve head (Figure 7-5). Seen emerging from the optic nerve are the retinal arteries and veins. On the temporal side of the optic nerve is a slightly darker region, known as the macula, and at the center of the macula is a tiny, but critically important area called the fovea. The fovea corresponds to the central 2° of the visual field, and because of its extremely high photoreceptor cell density, it supports the best visual acuity in the retina. The fovea is the most important part of the retina since it provides high-definition vision and is the focus of our visual attention. While damage to other areas of the retina may go unnoticed, damage to the fovea causes a debilitating loss of vision in that eye (Bron et al., 1997; Kaufman and Alm, 2003; Schwartz, 2004).

Refractive Errors and Their Correction

The most common cause of poor vision is an uncorrected refractive error. Ideally, the cornea and lens focus the optical image precisely onto the retina, but when refractive errors are present, the lens-to-retina focal distance is incorrect and the image is blurred.

Lower-order aberrations (defocus and astigmatism)

The largest refractive aberrations in the normal eye are defocus and astigmatism. These are sometimes referred to as the lower-order aberrations. Defocus includes the common refractive errors of *myopia* (near sightedness) and *hyperopia* (far sightedness). An eye that has no lower-order aberrations and therefore no refractive error is considered emmetropic (Figure 7-6a). In the case of myopia, the image comes to focus in front of the retina (Figure 7-6b). Distant objects are blurred for patients with myopia. In hyperopia the focal plane is behind the retina (Figure 7-6c). Depending on the degree of hyperopia, hyperopes usually have more difficulty focusing on

near objects. Astigmatism is a condition in which some of the eye's optical surfaces are curved like the side of an American football with greater curvature in one meridian (vertical) and a lesser curvature 90° away (horizontal). As a result, light in the eye forms a linear focus at one distance, a perpendicular linear focus at some greater distance and a blurred interval in between (Figure 7-6d), causing blurred vision for both far and near objects. The simplest refractive errors, such as myopia or hyperopia can be compensated in optical instruments such as binoculars or night vision goggles (NVGs) by adjusting the instrument's focusing ring. Astigmatism however, is more complex and requires customized correction with spectacles or contact lenses (Benjamin, 2006; Goss and West, 2002).

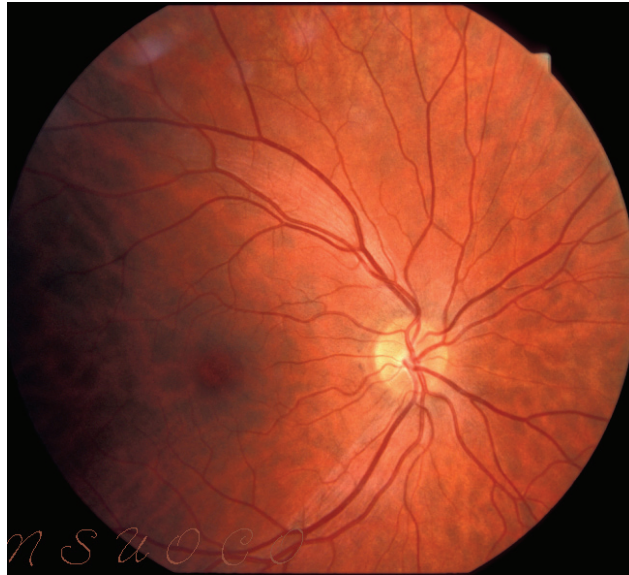


Figure 7-5. Photograph of a normal retina. This is what you would see if you looked into someone's right eye. The nose is to the right of the picture, the temple to the left (Copyright NSU Oklahoma College of Optometry; used with permission).

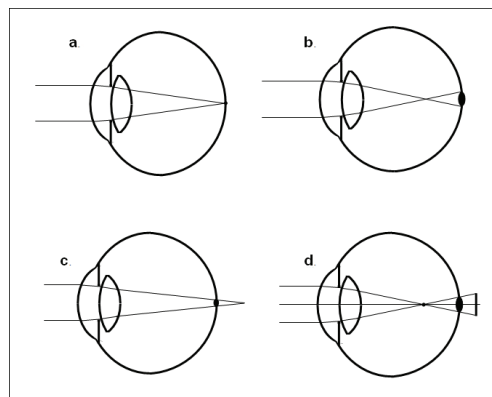


Figure 7-6. Refractive errors. In emmetropia (a) light focuses onto the retina. In myopia (b) light over-converges and forms a blur circle on the retina. In hyperopia (c) light under-converges and forms a blur circle on the retina. In astigmatism (d) some light over-converges, while some under-converges, resulting in a blur circle on the retina.

Higher-order aberrations

Higher-order aberrations are refractive errors that are more complex than myopia, hyperopia or astigmatism, and cannot be well corrected with conventional spectacles or contact lenses (Atchison and Scott, 2000; Campbell et al., 2004; Salmon and van de Pol, 2005). Fortunately, in most normal eyes, they are small and have little noticeable effect on vision (Thibos et al., 2002). The most common aberrations in the normal eye are coma, trefoil and spherical aberration (Salmon and van de Pol, 2006). When the lower-order aberrations are fully corrected, the presence of higher-order aberrations, along with light scatter in the eye cause symptoms of halos, glare, and reduced contrast sensitivity in some eyes (Chalita and Krueger, 2004; Mrochen and Semchishen, 2003).

Chromatic aberration

Refraction, which is the bending of light used by lenses to focus light, varies according to wavelength and is proportional to the wavelength. Therefore, any optical system using white light will be in focus for only one wavelength, while other wavelengths will be out of focus. This wavelength-dependent focusing discrepancy is referred to as chromatic aberration. In the case of the human eye, the focus difference between the shortest and longest wavelengths (longitudinal chromatic aberration) amounts to about 2 diopters (Thibos et al., 1990; Thibos, Bradley and Zhang, 1991). If the eye's optics form an in-focus retinal image for 555-nm light, slightly blurred, out-of-focus images from the other wavelengths will be superimposed. The net result will be a slightly more blurred image in white light, than in monochromatic (single wavelength) light. Fortunately, the eye's sensitivity to different wavelengths is biased toward middle wavelengths (see the CIE [Commission Internationale de l'Eclairage or International Commission on Illumination] $V[\lambda]$ function section below), and this significantly diminishes the adverse blur caused by chromatic aberration (Bradley, 1992). In addition, the lateral magnification of extended objects, or the location of peripheral objects, imaged on the retina, will vary with wavelength, and this can contribute to blur, especially in the peripheral retina. Chromatic aberration is not an issue for monochromatic displays or optical systems, but should be considered in any system that uses multiple wavelengths (colors) or white light. Chromatic aberration can also arise when optical instruments are not correctly centered relative to the eyes.

Spectacles and contact lenses

The most common way to correct refractive error is through the use of spectacles or contact lenses. In order to correct myopia, the correcting lens has to increase the divergence of light entering the eye, which effectively pushes the focus of the system back towards the retina. Myopia-correcting lenses, which diverge light, have a negative focal power and are referred to as *minus* lenses. For hyperopia the correcting lens must increase convergence of light such that the focus of the system is pulled forward towards the retina. Hyperopia-correcting lenses increase convergence and have positive focal power. They are therefore known as a *plus* lens. To correct astigmatism, a *cylinder* lens is used that has max power in one meridian and minimum power in the perpendicular meridian. This lens must be correctly oriented with the axis, which is the orientation of the eye's astigmatic refractive error (Benjamin, 2006).

Most eyes have a combination of defocus and astigmatism, so spectacle and contact lens corrections may contain correction for both kinds of refractive errors. Spectacles place this correction about 10 to 15 mm in front of the eye, whereas contact lenses are placed directly onto the cornea. There are advantages and disadvantages to each of these corrections, however in terms of compatibility with most head-mounted displays, contact lenses have the distinct advantage of providing a more unencumbered visual correction. That is not to say that contact lenses are the perfect solution since there are increased risks of eye infections and ocular discomfort with contact lenses, especially under austere or harsh environmental conditions (Benjamin, 2006; Bennett and Weissman, 2005).

Except for some recent developments in spectacle lens design, most spectacle lenses correct only lower-order aberrations. Besides correcting the lower-order aberrations of defocus and astigmatism, some aspheric contact lenses may correct spherical aberration (a higher-order aberration) for some patients. Currently the only contact lens type that can correct most higher-order aberrations of the cornea is a rigid contact lens. It covers and in effect, replaces the cornea as the anterior refractive surface of the eye. However, if higher-order aberrations are present in the intraocular components (posterior cornea and internal lens), these would not be corrected by rigid contact lenses. Efforts are under way to develop spectacles and contact lenses that are customized for each person's specific lower and higher-order aberrations.

Refractive surgery

Refractive surgery directly modifies the eye's optics in order to correct refractive errors. This can be accomplished through reshaping of the cornea (keratorefractive), implanting a lens in addition to the eye's natural lens (corneal inlay or phakic intraocular lens) or replacing the eye's natural lens (clear lens extraction). This often frees the patient from the need to wear spectacles. The most common refractive procedures are corneal, such as photorefractive keratectomy (PRK) or laser in-situ keratomileusis (LASIK). These techniques use a laser to reshape the cornea to either increase its power (to correct hyperopia) or decrease its power (to correct myopia). Keratorefractive surgery can also correct for astigmatism. Early forms of keratorefractive surgery often inadvertently increased higher-order aberrations and left patients with poor vision that was uncorrectable with standard spectacles or contact lenses. These aberrations were particularly problematic with large pupils, so they were most noticeable in low light (Bailey et al., 2004; Fan-Paul et al., 2002; Hammond, Puri and Ambati, 2004; Schallhorn et al., 2003; Yamane et al., 2004). Recent improvements in refractive surgery have decreased the risk of residual higher-order aberrations through the use of wavefront-guided customized corrections (Kaiserman et al., 2004; Krueger, Applegate and MacRae, 2004).

Testing the Visual System

A large number of tests are available to evaluate the visual system. They may be divided into: 1) tests of optical performance and 2) tests of visual performance. Clinical tests of optical performance usually measure refractive errors and enable doctors to prescribe the appropriate optical correction to restore a clear focus on the retina. Autorefractors (Figure 7-7) are tabletop instruments that objectively measure myopia, hyperopia and astigmatism, while newer instruments, known as aberrometers (Figure 7-8) measure all of these as well as higher-order aberrations. Optometrists and ophthalmologists have developed methods to determine spectacle prescriptions based on subjective responses from the patient, and subjective techniques are considered more accurate than autorefractors or aberrometry for measuring myopia, hyperopia or astigmatism. However, aberrometers provide the only practical way to measure higher-order aberrations in a clinical setting (Salmon and van de Pol, 2005). These tests measure only the optical portion of the visual system, while visual tests measure the performance of the entire system; that is the end result of both optics and neural processing. The most familiar visual tests measure visual acuity, contrast sensitivity, the visual field and color vision.

Spatial Vision

Spatial visual performance is defined here as how well we see static monochromatic images, while motion (temporal vision), color and depth perception will be considered separately.



Figure 7-7. Example of a clinical autorefractor. Figure 7-8. Example of a clinical aberrometer

Resolution visual acuity (visual acuity)

The most familiar spatial vision test is visual acuity, which uses the Snellen letter chart found in most doctors' offices. In order to correctly read a letter, such as an E, the patient must be able to resolve the separation between the strokes of the letter. This kind of visual task is therefore referred to as resolution visual acuity and the smallest gap that a person can resolve between the strokes of a letter is referred to as the minimum angle of resolution (MAR). A person with normal vision should be able to resolve a letter E with a 1.0-arc minute MAR. A standard Snellen acuity letter with a 1.0-arc minute MAR and height of 5.0 arc minutes (Figure 7-9) is 8.7 mm tall if the viewing distance is 6 meters (approximately 20 feet). If a person can read letters of this size, he is said to have a visual acuity of 20/20 in the United States, 6/6 in the United Kingdom, or 1.0 in many other countries. If the patient has worse-than-normal visual acuity, he will require larger letters.

If for example, the smallest letter he can read has an MAR of 10.0 arc minutes, which is ten times as large as a 20/20 letter, his visual acuity would be recorded as 20/200, 6/60 or 0.1. (Kaufman and Alm, 2003; Schwartz, 2004)



Figure 7-9. MAR and angular dimensions of a Snellen 20/20 letter E.

Table 7-1 lists different ways of recording equivalent visual acuities. Most visual clinical visual acuity charts use black letters on a white background (high contrast). In some cases subtle changes in vision may be detected more easily if the chart uses low contrast gray letters since low contrast is more difficult to see. Other special purpose charts may use only a limited set of letters, symbols or shapes to test visual acuity.

Contrast sensitivity

Contrast sensitivity provides a more comprehensive test of spatial vision than visual acuity. In a contrast sensitivity test, the patient views test patterns such as letters or stripes that vary not only in size and in contrast as well. Figure 7-10 shows one example of a contrast sensitivity chart with vertical stripes arranged in rows. On this

chart contrast decreases from left to right, while stripe size decreases from top to bottom. Although letters, stripes, or any other pattern could be used to test spatial vision, there are theoretical advantages to using gradient stripe patterns with transverse brightness profiles that change sinusoidally. These sine-wave grating patterns (Figure 7-10) are frequently used in vision research (Nadler, 1990; Schwartz, 2004).

Table 7-1.
Different ways to record equivalent visual acuities.

MAR	0.75	1.0	2.0	10.0
log(MAR)	-0.125	0	0.30	1.00
US Snellen	20/15	20/20	20/40	20/100
UK Snellen	6/4.5	6/6	6/12	6/60
Decimal	1.33	1.0	0.5	0.1
Note: The left column shows the best visual acuity scores. The shaded column indicates the standard for normal well-corrected vision, and the two right columns indicate worse-than normal vision.				

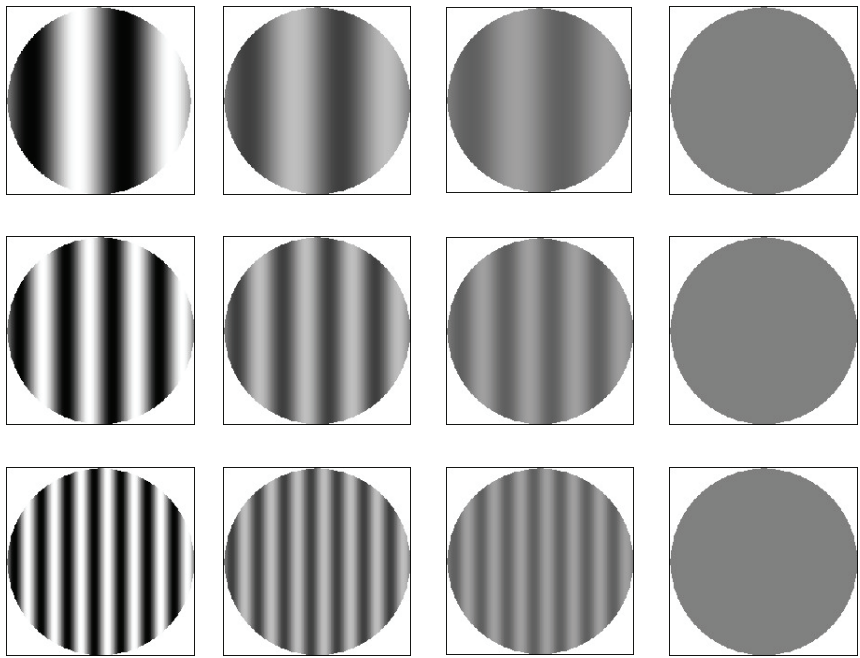


Figure 7-10. Clinical contrast sensitivity charts use targets such as these to test vision. In this simple chart, spatial frequency varies from top to bottom with 2, 4 and 7 cycles in Rows 1, 2 and 3 respectively. Contrast decreases from left to right, with approximate values of 1.0, 0.5, 0.25 and 0 in Columns 1, 2, 3 and 4, respectively. Actual clinical test charts usually include more spatial frequency and more contrast levels. They are designed to measure the minimum contrast a person can see for each spatial frequency.

The two key parameters of a sine wave grating that affect its visibility are stripe width and contrast. Stripe width is specified by the number of repeating light/dark cycles per degree of visual angle, as seen from the eye. Broad stripes have fewer cycles per degree, and are therefore said to have a low spatial frequency. Narrow stripes

have more cycles per degree, or a higher spatial frequency. Low spatial frequency gratings (broad stripes) test how well we see large objects, while high spatial frequency gratings (narrow stripes) test how well we see small objects. A contrast sensitivity chart includes gratings with a range of spatial frequencies representing the range of sizes visible to a normal human eye. A high-contrast 30-cycles-per-degree grating corresponds in size to the 20/20 letter on a Snellen eye chart, and should be readable for a person with normal vision.

Contrast is the other key parameter that affects visibility. Low contrast is always more difficult to see than high contrast. Vision scientists define contrast according to the Michelson formula (Equation 7-3), where variables L_{\max} and L_{\min} refer, respectively, to the luminances of the brightest and darkest portions of the test pattern. Michelson contrast has a maximum value of 1.0, which is the contrast of a black object against a pure white background in the case of a typical visual acuity chart, or the contrast of bright green symbology on a black background as in an aircraft heads-up display. The minimum contrast value is 0, which is the contrast of a gray letter against an equal-luminance gray background – that is, a uniform gray field.

$$C = (L_{\max} - L_{\min}) / (L_{\max} + L_{\min}) \quad \text{Equation 7-3}$$

In contrast sensitivity testing, we determine the minimum contrast (contrast threshold) a person can see across a range of spatial frequencies (sizes). A person with good vision is capable of seeing low contrast, and would have a low contrast threshold. A high threshold indicates poor vision. Contrast sensitivity is computed as the inverse of the contrast threshold. High contrast sensitivity (low threshold) indicates good vision, and low contrast sensitivity indicates poor vision. Figure 7-11 presents a typical contrast sensitivity function. It peaks at about 4 cycles per degree, and drops off on either side. On the high frequency side, the curve steadily declines to zero. The spatial frequency at that point is referred to as the cut-off frequency, and represents the resolution limit of that visual system. A person with excellent vision would be able to resolve 40-60 cycles per degree.

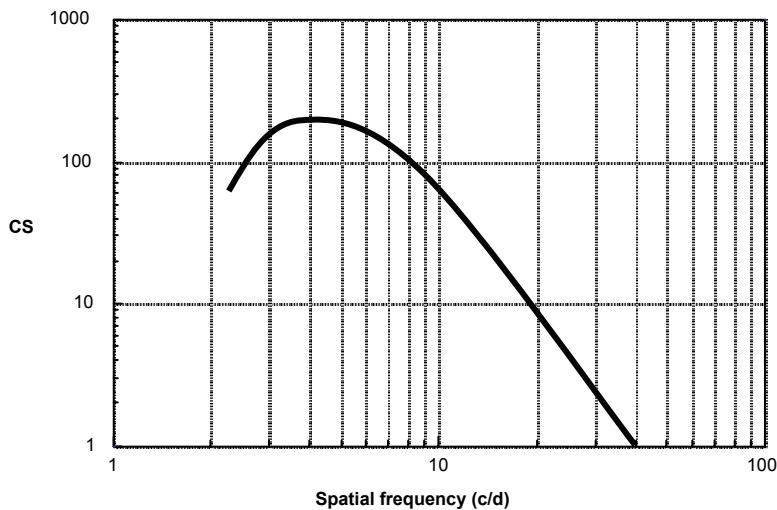


Figure 7-11. A typical contrast sensitivity function.

New technologies are making it possible to correct optical errors more perfectly than ever before. This raises an interesting question: “How well could a person see if he had perfect optics?” Theoretically, with a large pupil, the eye’s optics should be capable of imaging approximately 200-cycle-per-degree patterns onto the retina, (Atchison and Smith, 2000) but because of the size of retinal photoreceptors cells, the retina cannot resolve spatial frequencies greater than about 75 cycles per degree (Applegate, Thibos and Hilmantel, 2001). This corresponds to

a Snellen visual acuity of 20/8 (American notation), which would be four rows better than 20/20 on a standard chart.

Although most visual scenes contain a complex mix of spatial frequencies and contrasts, the contrast sensitivity function (CSF) characterizes the basic spatial vision capabilities of the visual system by testing at discrete spatial frequencies. In some respects it resembles the modulation transfer function (MTF) used in optical engineering, however it differs from an optical MTF because the CSF also takes into account neural processing by the brain. Various optical or pathological problems can affect vision, and they can affect different aspects of the CSF to different degrees. For example, small refractive errors mainly reduce the CSF in the high spatial frequencies only. This makes small objects more difficult to see, but large objects are unaffected. A cataract or even a dirty helmet visor can cause poor vision across a broader range of spatial frequencies. Cockpit instruments, especially those used at night provide high contrast, and are therefore easy to see. However, other important visual information, for example, maps in the cockpit, or outside terrain features, personnel or equipment, may have low contrast, which makes them difficult to see.

Since high spatial frequencies and lower contrasts are harder to see, optical devices can improve vision by decreasing the spatial frequencies of images, increasing contrast or both. Magnification is one way to decrease the spatial frequency of objects. Another simple way to decrease spatial frequency is to move closer to the object. Visibility of computer monitors or cockpit displays can be improved by increasing contrast. Spectacles or contact lenses correct optical blur, which improves contrast at high spatial frequencies thereby making small objects easier to see.

Vernier acuity

Another important spatial visual task is the ability to detect a difference in the relative position of two objects. For example, what is the smallest angular offset of one line, relative to the other that the visual system can detect (Figure 7-12)? This kind of task is referred to as Vernier acuity, and under ideal conditions we are capable of detecting angular offsets as small as 10 arc seconds. This is equivalent to detecting a 1-mm offset at a distance of 20 meters. Because Vernier acuity is so good, it is sometimes called hyperacuity. High precision measuring devices sometimes use tick marks or images that an observer must align, in order to take advantage of Vernier acuity. Vernier acuity is also used by naval aviators to verify the correct glide path during aircraft carrier landings (Figure 7-13). Vernier acuity is also important for aiming weapons since the shooter must aligning the back sight with the front sight and target.



Figure 7-12. Vernier acuity example. Which line is higher?

Peripheral Vision

Unless otherwise specified, we assume that visual acuity, contrast sensitivity and most other vision tests are measuring central or straight-ahead vision. In this case, the object of interest is imaged onto the part of the retina known as the fovea. Although the fovea accounts for only the central 2° of the visual field, it provides the majority of the visual information that occupies our visual. High photoreceptor density in the fovea optimizes resolution and makes 20/20-or-better visual acuity possible. Photoreceptors are more sparsely placed in the peripheral retina, where visual acuity is worse, usually in the range of 20/200, which is ten times worse than foveal vision.

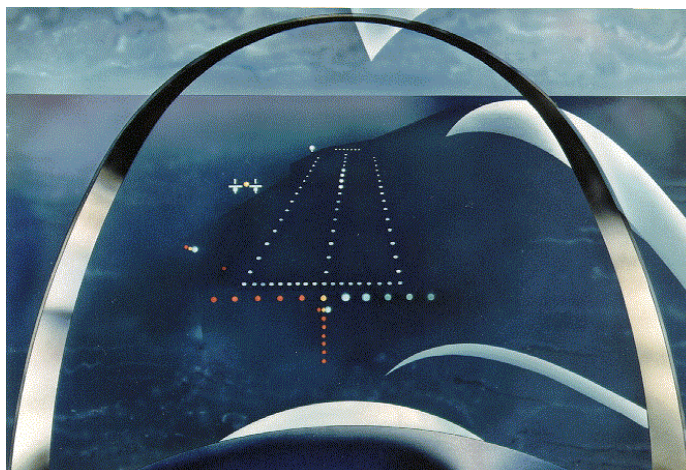


Figure 7-13. Navy pilots judge the alignment of landing lights to verify their glide path during a carrier landing, a Vernier alignment visual task. (Used with permission from NAVAIR Lakehurst; <http://www.lakehurst.navy.mil/nlweb/cols.gif>)

Although visual acuity declines peripherally, peripheral vision is important, especially for detecting large objects or moving objects. With static straight-ahead gaze, the monocular visual field extends as far out as 50, 60, 70 and 90° in the superior, nasal, inferior and temporal directions, respectively. As shown in Figure 7-14, with both eyes fixating straight ahead, the full extent of the binocular visual field is about 180°. Since each eye's visual field extends 60° nasally beyond straight-ahead gaze, the two monocular visual fields have considerable overlap. This means that objects located within the central 120° are seen by both eyes, thereby giving us the advantages of binocular vision. Objects located in the far periphery to the right and left are seen only by one eye. (Anderson and Patella, 1999)

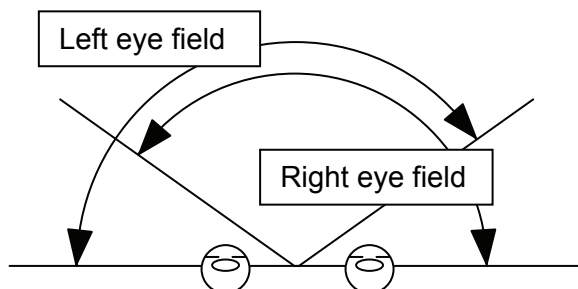


Figure 7-14. Top view of each eye's visual field. The right and left eye visual fields extend from about 90° temporal, across the midline and about 60° into the opposite field. The horizontal extent of each eye's field is about 150°. The central 120° of the two fields overlap. The far temporal periphery of each eye's field is seen by one eye.

Although unobstructed eyes may have the monocular or binocular visual fields limits described above, optical devices, such as NVGs usually restrict vision to a narrower field. However, by scanning with the eyes and moving the head or body, the relatively narrow 40-degree field-of-view of NVGs can cover nearly 360° of visual space. External obstructions such as window frames, seats, or shoulder harnesses that restrict movement are also factors that limit the effective field-of-view.

Although visual resolution is worse in the periphery, some aspects of peripheral vision are better than central vision. We can usually detect motion better in the periphery, and the mid-peripheral retina, about 20° outside the

fovea, is actually better than the fovea for seeing faint objects in the dark. With this in mind, personnel who must detect faint objects at night should be taught to look slightly to the side of rather than directly at the objects they are trying to see.

Visual Adaptation to High and Low Illumination

Among the neurons in the retina are two classes of photoreceptor cells, the *rods* and *cones*, which start the visual process by responding to light in the image created by the eye's optics. Using a complex biochemical process known as phototransduction, the photoreceptors convert optical energy into electrophysiological signals that are relayed to the brain. The rods and cone photoreceptor cells differ in terms of their intracellular structure, and range of sensitivity. The presence of these two photoreceptors systems enable the visual system to operate over a wide range of light levels (Kaufman and Alm, 2003; Schwartz, 2004).

Scotopic vision

Rods support vision in low light (*scotopic* vision) and are designed to maximize photon capture. They are absent in the fovea but present in the rest of the retina. Since there are no rods in the fovea, under scotopic conditions, such as at night, the central 2° of the visual field becomes a tiny blind spot. The rods are designed to capture light when photons are sparse, and scientists have found that a rod cell is capable of responding to a single photon of light. Perceptual awareness requires simultaneous absorption of at least 10 photons (Cornsweet, 1970). The scotopic system operates from nearly complete darkness up to luminance values of about 1 candela/m². Rods photoreceptors do not contribute to color perception. Because of the distribution of rods and their supporting neurons, scotopic visual acuity is poorer than cone-mediated acuity. On the other hand, the rod system is better at integrating light from a larger area of the retina, and it therefore provides vision in low light, below the threshold for cones. As illumination increases and approaches the upper limit for the rods, the cones begin to work. For intermediate light levels both rods and cones are working. Vision in this range of illumination is known as *mesopic* vision. As illumination increases above the mesopic level, the rods become saturated and cease to function. We then transition to cone-mediated, that is, *photopic* vision. The output of most NVGs is sufficiently bright that the eye's response is in fact cone-mediated, which has implications for vision in unaided areas of the visual field at night (see below).

Photopic vision

Cones are present throughout the retina, but are most highly concentrated in the fovea and more sparsely distributed in the periphery. At the center of the fovea, cone density is about 120,000 cells/mm² (Bron et al., 1997), and provides distinct input to the visual center in the brain. This allows for high-resolution vision of at least 20/20. In the peripheral retina, cone density decreases, and input from cones is pooled. This limits visual resolution and visual acuity to about 20/200. In addition to providing high-resolution central vision, the cone system supports color vision. Because of their structure, cones capture light most effectively if rays enter straight on, that is, perpendicularly to the retinal surface. Light rays striking at wider angles stimulate the cones less efficiently, a phenomenon known as the Stiles-Crawford effect. Because of this, light rays entering the peripheral pupil appear less bright than rays entering centrally. A benefit of the Stiles-Crawford effect is that light scattered within the eye has little effect on cone vision. Eventually illumination becomes so high that the cones become saturated and vision fails.

It is interesting to note that personnel using NVGs may be using mesopic and photopic vision for the central 40° of their visual field, while depending on scotopic vision to scan for objects in the far periphery.

The CIE $V(\lambda)$ function

Both rods and cones are sensitive to a wide range of wavelengths, but sensitivity varies for different wavelengths (Figure 7-15). Both rod and cone sensitivities peak near the middle of their respective ranges. In terms of absolute sensitivity, the rods are more sensitive than the cones. Figure 7-15 also shows that the scotopic (rod) sensitivity spectrum peaks at shorter wavelengths than the photopic (cone) sensitivity spectrum. Because of this, as illumination decreases and we transition from photopic to scotopic vision, we may perceive that shorter wavelength hues become relatively brighter while longer wavelength hue become less bright, a phenomenon known as the Purkinje shift. The photopic curve in Figure 7-15 is referred to as the CIE luminous efficiency curve, or $V(\lambda)$ function (Stockman et al., 2006). It defines the how efficiently the each wavelength stimulates the vision of a normal human observer, and is therefore foundational for the field of photometry. Photometry defines standard units for illumination and luminance, which simply put, specifies perceived light intensity. Illumination quantifies the amount of light falling on an area. A basic metric unit for illumination is the lux (lumens/m²); the English unit is the foot-candle (lumens/ft²). Luminance quantifies the amount of light emitted from an extended source. A basic metric unit for luminance is the nit (candelas/m²); an English unit is the foot-Lambert (1/π candelas/ft²) (Schwartz, 2004).

Dark adaptation

Within their working ranges, rods and cones must adapt to changes in light level. When illumination increases (light adaptation), the photoreceptors become less sensitive to light. When illumination decreases (dark adaptation), they become more sensitive. Cones dark adapt more quickly than rods and reach their maximum sensitivity after about 15 minutes in the dark. Rods, on the other hand require about 40 minutes to fully dark adapt and reach maximum sensitivity. After complete dark adaptation, exposure to any light begins the process of light adaptation and visual sensitivity declines. If a dark-adapted person needs to use a light, yet hopes to preserve dark adaptation, the loss of sensitivity can be minimized by using a long-wavelength red light. Long wavelengths are relatively poorly absorbed by rods, so red light has minimal impact on rod dark adaptation. Meanwhile, cones are about equally sensitive to rods at long wavelengths, so they can contribute to vision in low light (Kaufman and Alm, 2003; Schwartz, 2004).

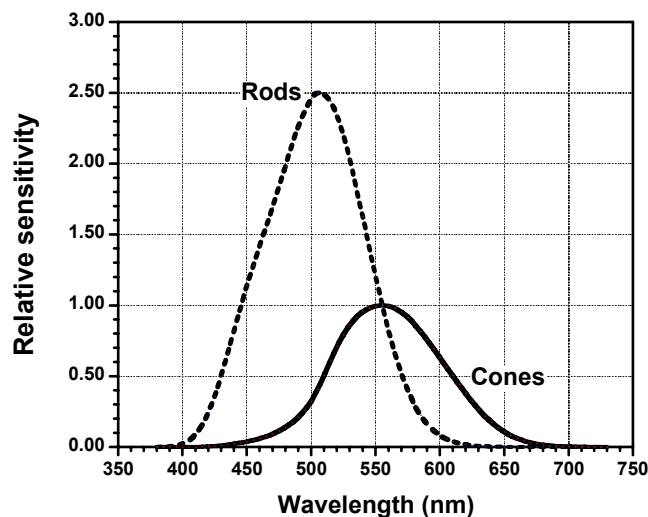


Figure 7-15. Relative sensitivity of the rod (scotopic) and cone (photopic) systems as a function of wavelength.

Color Vision

Color is a critical feature of vision since it helps us better discriminate objects, such as different teams, medical test results or cockpit data. Color describes the sensation created by the visual system primarily based on the wavelength absorbed by the cones. Someone once said, “Color is not a property that inheres in external objects but is rather an internal construct of the individual, dependent on the wavelength composition of light entering the eye and on the structure of the eye and nervous system” (Swanson and Cohen, 2003). Therefore, although different wavelengths of light exist in the physical world, color exists only in the mind of the beholder.

Hue, saturation, brightness

As was mentioned earlier in this chapter, the human visual system is sensitive to electromagnetic radiation with wavelengths between approximately 700 and 400 nm, which corresponds to hues ranging from red, orange, yellow, green, blue and violet, which is near 400 nm. The three basic characteristics of a color are its *hue*, *saturation*, and *brightness*. Hue refers to the aspect of color that most obviously distinguishes one wavelength from another, and is often used synonymously with the word “color.” For example, “red,” “green” and “blue” refer to different hues. However any hue can vary in appearance because of differences in color saturation, which describes how pure or vivid a particular hue is. For example, a highly saturated version of red looks deep red while a desaturated version looks pink. Two colors with the same hue and saturation can also look different due to differences in brightness.

L, M and S cones

Color perception is based on the ability to discriminate wavelengths, and this is possible because the retina contains three types of cone photoreceptors, each of which responds to a different range of wavelengths. Figure 7-16 shows an example of how the three cones types, known as S, M and L cones, are distributed in a portion of one person’s retina. (Roorda et al., 2001; Roorda and Williams, 1999) The three classes are designated S, M and L cones because their peak sensitivities are located, respectively, in the short, middle and long wavelength ranges. Although they have peak sensitivities at different wavelengths, each absorbs a broad band of wavelengths across the visible light spectrum, as shown in Figure 7-17. The overlapping across different absorption spectra makes it possible to uniquely encode any wavelength by the ratio of three cone responses. The three cones send their signals into a complex network of neurons within the retina that further process the wavelength and brightness information and send it to the brain, which completes our perception of color (Schwartz, 2004).

The CIE (Commission Internationale de l’Eclairage or International Commission on Illumination) color specification system

Just as our visual system can sense any color based on the response of three cone types, it is possible to create a wide range of colors by mixing three primary colors. For example, TV and computer monitors simulate different colors by mixing red, green and blue colored lights. This is an example of additive color mixing. Subtractive color mixing occurs when pigments rather than lights are mixed to create other colors. Three primaries that are often used for subtractive color mixing, as is done in printing, are yellow, cyan, and magenta.

Different color specification systems have been developed, but the most popular is 1931 CIE color specification system. It matches color by the additive mixture of three primaries known as X, Y and Z. The system has been designed so the relative proportion of each primary in a mix is represented by chromaticity coordinates x , y and z , the sum of which always add up to a value of 1.0 for each wavelength hue. If any color’s x and y coordinates are known, the z value can directly be computed, so the x and y chromaticity coordinates are sufficient to specify any color. By plotting the x and y coordinates for any wavelength hue, we can generate an arc

of points that represents every color of the spectrum, as shown in Figure 7-18. This is the CIE chromaticity diagram, and is frequently used in science and engineering to analyze and perform calculations with color. The points along the arc represent all colors of the spectrum, and points within the arc represent all other colors that can be created by any mixture of the spectral hues. The straight border along the bottom of the CIE chromaticity field represents various shades of purple that can be created by mixtures of violet and red. Pure white has chromaticity coordinates $x=0.33$, $y=0.33$, $z=0.33$ since it is made up of equal amounts of the three primary lights (Schwartz, 2004; Stockman et al., 2006). Another widely used color specification system is the CIE Lab system. It may be derived from the CIE standard color designation by transforming the original x , y and z coordinates into three new reference values known as L , a and b . This transformation creates a color coordinate system that better expresses color differences as perceived by a normal eye (Agoston, 1979; McLaren, 1976).

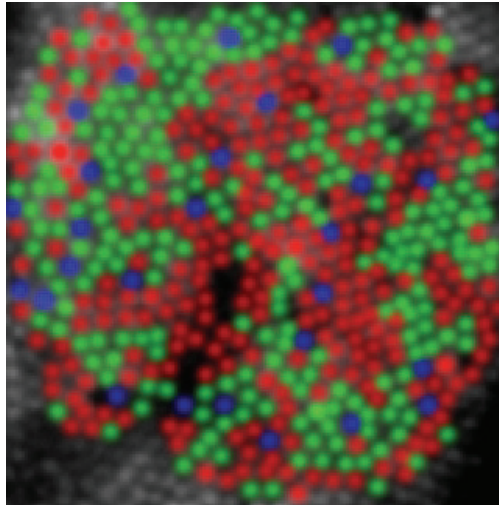


Figure 7-16. Distribution of S, M and L cones in the paracentral retina of one subject. Blue, green and red dots respectively show the locations of S, M and L cones in a $136 \times 136 \mu\text{m}$ (0.5×0.5 degree) region on the retina. Calculated from data provided by Austin Roorda, and available in a downloadable Excel spreadsheet at: <http://vision.berkeley.edu/~roordalab/>

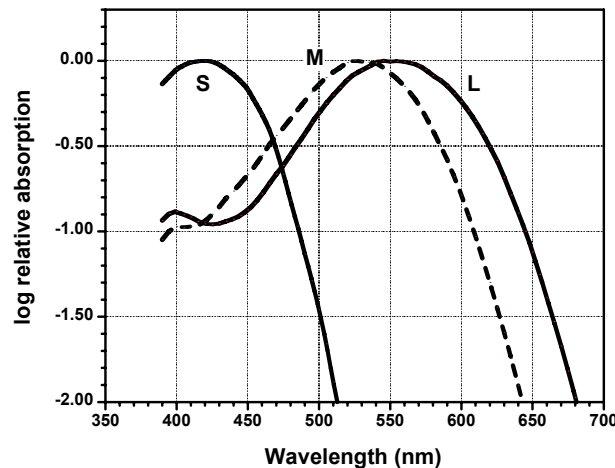


Figure 7-17. Relative absorption spectra of the S, M and L cones based on the Stockman and Sharpe 2000 data set, downloadable from: <http://www.cvrl.org/>

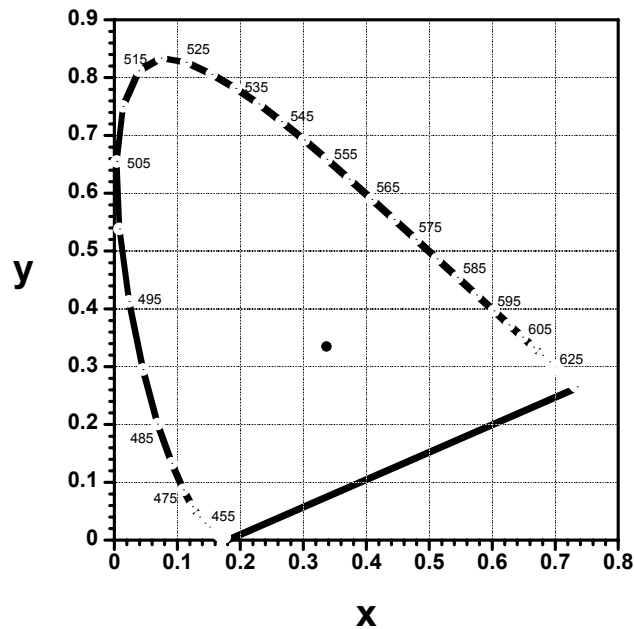


Figure 7-18. The CIE chromaticity diagram. Labels on the curve indicate wavelength in nanometers (nm). The dot indicates the coordinates for pure white.

Color blindness and abnormal color vision

Cataracts, other diseases or toxicity can cause anomalous color vision, but most color vision defects are hereditary. Hereditary color anomalies are classified into three categories based on the cone type that is affected. Patients with problems in the L, M or S cones are respectively referred to as *protans*, *deutans* and *tritans*. Absolute protans have no L cones, while patients with mild protanomalous vision experience a less severe color anomaly due to defective L cones. Similarly M-cone defects are subdivided into deuteranopia, where the M-cones are absent, or deuteranomaly, where they are present but anomalous, and S-cone defects are likewise divided into tritanopia and tritanomaly. Hereditary color vision anomalies affect about 8% of males but only about 0.4% of females. Among them, deuteranomaly is the most common, affecting 5% of males. Both protans and deutans have difficulty discriminating long and middle wavelength colors. This range of wavelengths includes the hues red and green, so both protans and deutans are sometimes referred to as having red-green color anomalies. Interestingly, although color blindness and color anomalies predominantly affect males, men with the defective gene inherit it from their mothers. Since red-green color anomalies are not rare, affecting about 8% of the male populations, engineers who plan to incorporate color into displays or signals should be careful to avoid colors that can be confused by red-green color anomalous patients. These patients have difficulty discriminating hues such as red, orange, yellow and greenish-yellow, but would be able to discriminate red from blue. To ensure that they can distinguish different items, they should use appropriate colors or other visual cues, such as brightness, flicker or different-shapes to avoid confusion.

Many color vision tests diagnose anomalies by presenting colors that confuse certain categories of color-anomalous patients. Since red-green anomalies are the most common, many color vision tests only diagnose protans and deutans from normals, but do not distinguish between them. The Ishihara color vision plates (Birch, 1997) (Figure 7-19) display a colored number embedded in a background made up of another color. The colors are selected from among those that are confused by color anomalous persons. Depending on which colors are used, it's possible to differentially diagnose protans, deutans and tritans. One of the most well-designed and easy

to use color vision tests is the HRR test (named after the designers, Hardy, Rand, Rittler,). Like the Ishihara test, it consists of a book of plates with colored figures embedded in a gray background. It can diagnose all three classes of color anomalies as well as grade their severity (Bailey et al., 2004). Some tests, such as the widely used D-15 test, require patients to arrange color samples in a particular order. Another test, sometimes used to screen aviators, the Farnsworth Lantern test (Figure 7-20), presents patients with red, green or white lights, which they must identify. There is no effective cure or treatment for hereditary color vision defects, but patients with color vision anomalies often learn to compensate and may have little problems identifying colored objects in natural environments. They are more likely to make mistakes, however, when viewing man-made signal lights or symbology (Benjamin, 2006; Schwartz, 2004).

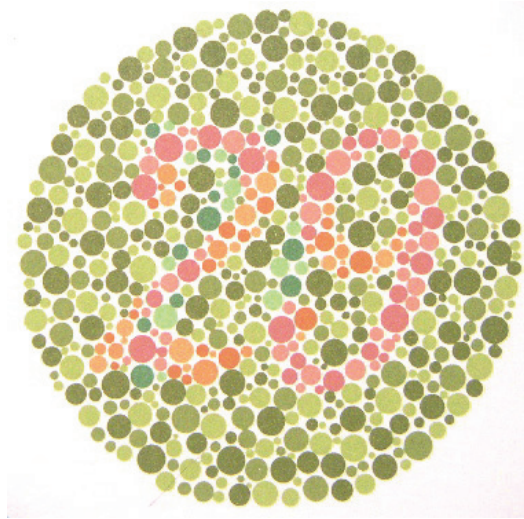


Figure 7-19. One page from the well-known Ishihara color vision test book. People with certain color anomalies have difficulty reading the number (29).



Figure 7-20. In the Farnsworth Lantern test, the patient must identify the color to two lights, each of which may be red, green or white.

Accommodation

Accommodation is the auto focusing mechanism of the eye that allows us to clearly see objects at different distances. By increasing or decreasing its curvature, the eye's internal lens changes the eye's refractive power thereby enabling it to refocus. To see near objects, the eye requires more refractive power, and less power is needed to focus on distant objects. The internal lens is suspended by a system of fibrils that originate from the ciliary body, an annular muscle lining the inside of the eye just behind the iris. In the non-accommodative state, the emmetropic eye is focused for an infinitely distant object. The ciliary muscle is relaxed and relatively flat, pulling outward on the zonular network and lens. This outward radial tension pulls on the lens periphery and flattens the anterior surface, causing less refractive power (Figure 7-21). During accommodation, when the eye focuses at near, the ciliary muscle, a sphincter, contracts, bulges and shortens its internal radius. This releases tension on the zonules, allowing the lens to "bulge" or increase its anterior surface curvature and refractive power (Benjamin, 2006; Goss and West, 2002).

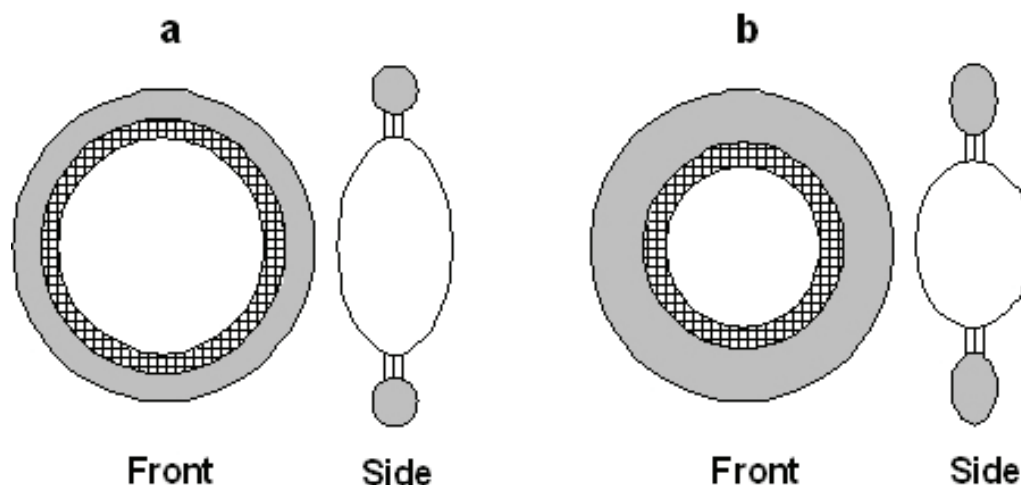


Figure 7-21. Schematic diagram of Helmholtz' theory of accommodation. In the unaccommodated state (a), the ciliary muscle (gray annulus) is relaxed and has a large inner diameter. This pulls the crystalline lens (white) flat, via the connecting zonular fibrils (lines). During accommodation (b), the ciliary muscle, which is a sphincter, flexes and decreases its inner diameter. This allows the crystalline lens to bulge, thereby increasing its focal power.

The accommodative triad

When focusing on near objects, three actions occur simultaneously: the eyes rotate inward (converge), the pupils constrict and the lenses of both eyes increase in power (Benjamin, 2006; Goss, 1995; Goss and West, 2002). Convergence orients both eyes toward the near object of interest so that its image is focused on each eye's fovea. Pupil constriction increases the eye's depth of focus, which improves clarity of near objects. Finally, the lenses of each eye change shape to accommodate; the amount of accommodation is generally symmetrical between the two eyes. These three components of accommodation are known as the accommodative triad or near reflex and are neurologically coupled at the Edinger-Westfal (EW) nucleus in the brain. It is therefore possible to drive lens accommodation and pupil constriction just by converging the eyes. Alternatively a stimulus to accommodation can cause the eyes to converge. This near reflex can work against clear, comfortable vision in binocular or biocular head-mounted displays when there are imbalances in convergence or divergence demands on the eyes due to misalignment of oculars or other optical components. Difficulties can also arise when there is an optical

accommodative demand in the system due to excessive minus power in one or both oculars; this can drive the eyes to converge and lead to fatigue and/or double vision.

Stimulus to accommodation

Blur is the primary stimulus for accommodation. Retinal blur stimulates the EW nucleus, which then stimulates accommodation. In the absence of any other information, the eye will increase accommodation to make the image on the retina clear. If increasing accommodation further blurs the image, a feedback loop changes the accommodative response from positive to negative, decreasing accommodation. If this were the only mechanism to determine the direction of accommodation, the eye would constantly search for a focus when regarding objects at different distances (or levels of blur). As noted above, convergence of the eyes also stimulates accommodation, thereby assisting the optically driven accommodative mechanism. Longitudinal chromatic aberration of the eye also contributes to accommodation. Since short wavelengths focus closer to the lens than long wavelengths, the spectral composition of the blur provides directional information for the accommodative response. In head-mounted displays where some of the additional cues to accommodation, such as color and convergence demand, are not present, the accommodative system may be less precise and the visual system may become more fatigued.

Night myopia

If no objects are visible, such as in the dark, or when viewing featureless haze outside a cockpit, the eyes will have no optical input to stimulate accommodation. In these situations, the accommodative system does not relax, but rather tends to accommodate slightly and focus for an intermediate distance of about one meters. This dark focus of accommodation causes temporary myopia (night myopia) and will cause distant objects, should they appear, to be slightly blurred. Some pilots who frequently fly at night may need a slightly more myopic eyeglass prescription for night flying to compensate for night myopia.

Testing accommodation

The amplitude of accommodation can be determined in a number of ways. The simplest technique involves presenting a small target at a comfortable distance from the eye and moving it closer until a clear focus cannot be maintained. The near point of accommodation may be recorded in terms of cm from the eye or converted to optical power in diopters by computing the inverse of the distance in meters. Accommodation can also be measured using divergent (minus) lenses of increasing power placed in front of the eye while a distance target is observed. Since the eye accommodates (adds plus focal power) to counter the minus lens, the amount of accommodation is equivalent to the highest power lens that can be cleared. Similarly, some instruments measure accommodation by determining the near point through translation of a target or through changes in the instrument's optical power.

Presbyopia

The ability to accommodate gradually decreases with age (Figure 7-22) (Atchison, 1995; Koretz et al., 1989). Young children may have 15 to 20 diopters of accommodation, giving them the ability to see objects clearly as close as 5 cm from the eye. As we age, the lens continues to grow, becoming denser and less flexible. The result is a decreasing ability to focus on near objects so that by age 20, accommodative ability will have declined to approximately 12 diopters so the near point will have receded to about 8 cm from the eye. By age 40, accommodation may have decreased to 4 or 5 diopters causing further regression of the near point to about 20 to 25 cm from the eye. Around age 45, the loss of accommodation reaches the point where reading and other close work becomes difficult without a reading correction for most people. By age 60 the lens becomes inflexible and

unable to accommodate. This is complete presbyopia and requires an optical correction such as reading glasses or bifocals with a power in diopters equal to the inverse of the reading distance (e.g. +2.50 diopters to focus on objects 40 cm from the eye) (Benjamin, 2006; Bennett and Rabbetts, 1991; Goss and West, 2002).

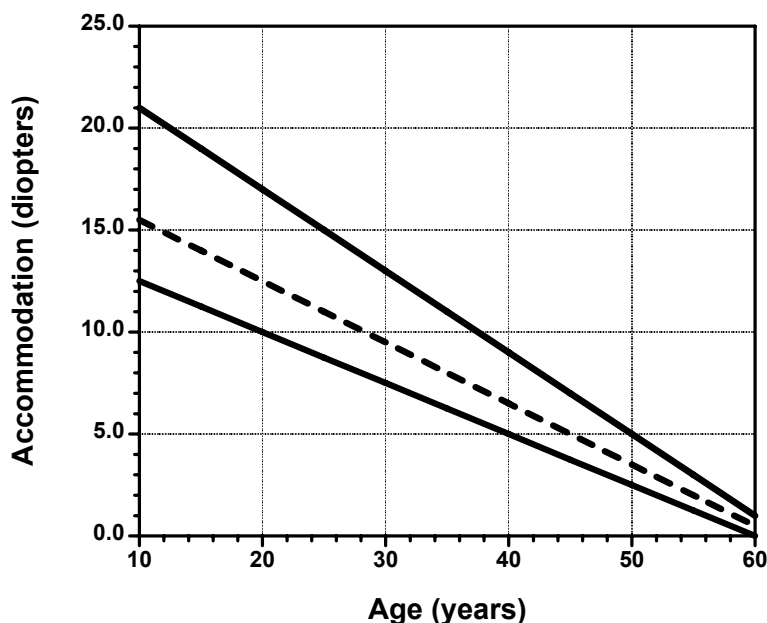


Figure 7-22. Maximum, average and minimum amplitude of accommodation expected with age, according to Hofstetter's formulas.

Presbyopic corrections

Since presbyopia is a condition where distance vision is maintained while the ability to see near is impaired, the goal in correcting presbyopia is to provide additional power for near only. For presbyopic emmetropes (no distance refractive error) or presbyopes wearing contact lenses to correct distance vision, the simplest solution is a pair of reading glasses. The drawbacks to this solution are few, but could be significant depending on the circumstances. Reading glasses provide focus at near or intermediate distances only, therefore distance objects will appear blurry through these lenses. Since the glasses have to be removed to see distant objects, they can be easily misplaced and may not be readily available when needed. Bifocals or multifocals can be a solution for myopes, hyperopes or astigmats who need a distance and near correction and for emmetropes who do not want their distance vision blurred by reading glasses. The top portion of the multifocal lens is designed for distance vision and the lower portion of the lens has either a segment of additional power for near, called an *ADD*, or a gradual increase in power from top to bottom, called a *progressive* multifocal (Benjamin, 2006).

Contact lens corrections for presbyopia include monovision, where one eye is corrected for distance and the other eye is corrected for near, or multifocal, where different zones in the contact lens provide distance or near focus. In monovision, the brain must adapt to one eye being dominant for distance and the other eye being dominant for near. While both eyes contribute to vision at both distances, there is a reduction in visual quality in the eye not focused at the particular distance. In general, about 70% of patients who are fit with monovision successfully adapt to it (Westin, Wick and Harrist, 2000). Multifocal contact lenses are most often designed to provide simultaneous vision, either through the use of discrete distance/near zones or through an aspheric design that gives a continuous, distance-to-near power change over the lens area. When the eye is looking at distant objects, the portion of the lens devoted to distance vision focuses these rays onto the retina; at the same time, near

objects will be focused onto the retina by the near optics. Most simultaneous design lenses compromise image contrast due to the “splitting” of focal power for both far and near. A translating multifocal contact lens is another solution. It has discrete far- and near-focus zones that shift as the wearer changes gaze from far (up gaze) to near (down gaze). The lens rests on the lower lid and slides upward when the eyes look downward, thereby centering the near zone over the pupil. Translating lenses work best as rigid gas permeable (hard) lenses, rather than as soft contact lenses and are therefore less popular (Bennett and Weissman, 2005).

Surgical procedures to correct presbyopia are on the increase. PRK or LASIK can be used to create a monovision correction by leaving one eye slightly near-sighted and correcting the other eye for distance. These procedures can also be used to create an aspheric corneal surface that works much like an aspheric contact lens that provides simultaneous distance and near vision. Intra-corneal inlays are in development and include small lenses that provide a central “reading” power as well as small aperture devices that increase the eye’s depth of focus. Intraocular procedures include small accommodating lenses that are surgically implanted inside the eye. Two designs include intraocular lenses that shift forward to increase the near focus of the eye, and multifocal lenses that provide simultaneous vision. The intraocular lenses require removal of the eye’s internal lens and are usually reserved for patients undergoing cataract surgery (Krueger et al., 2004).

The Eye’s Temporal Responsiveness

Although it is often studied as a separate topic, the temporal response of the visual system is strongly influenced with the luminance, spatial, color and surrounding aspects of a stimulus and whether it is located in the central or peripheral visual field. Temporal considerations are important even for a task as simple as light detection, because detection requires that sufficient light be collected over time, a phenomenon known as temporal summation. Temporal resolution, that is, the ability to resolve two visual stimuli separated by time as two, is another fundamental aspect of temporal vision. Flickering lights, which are simply a series of repeat presentations, are also used to study temporal vision. If the rate of flicker is high enough, the visual system will no longer be able to resolve the individual flashes and will perceive a steady light. The rate at which the flicker fuses into a steady perception is known as the critical flicker fusion (CFF) frequency. Temporal contrast sensitivity is determined by changing the contrast level of targets and then determining the CFF for each level. When you combine temporal contrast sensitivity with spatial contrast sensitivity you obtain a fairly complete representation of the limits of the human visual system (Van Hateren, 1993). Motion processing is a special case of temporal vision where the spatial position of the object changes with time, either due to movement of the object across the field of regard or movement of the observer’s eyes or head with respect to the object, which causes the image to move on the retina (Kaufman and Alm, 2003; Schwartz, 2004).

Temporal summation and the critical duration

When attempting to detect a dim light, there is an inverse relationship between stimulus intensity (brightness per unit time) and its duration up to a critical duration. That is, a dimmer light must be left on longer in order to be seen, while brighter lights can be detected with shorter durations. This is referred to as time-intensity reciprocity and is described by *Bloch’s law*

$$Bt = K$$

$$\text{Equation 7-4}$$

where B = luminance, t = duration, and K = a constant value.

If the time the stimulus is left on exceeds the critical duration, the intensity required for detection remains constant. This relationship is depicted schematically in Figure 7-23.

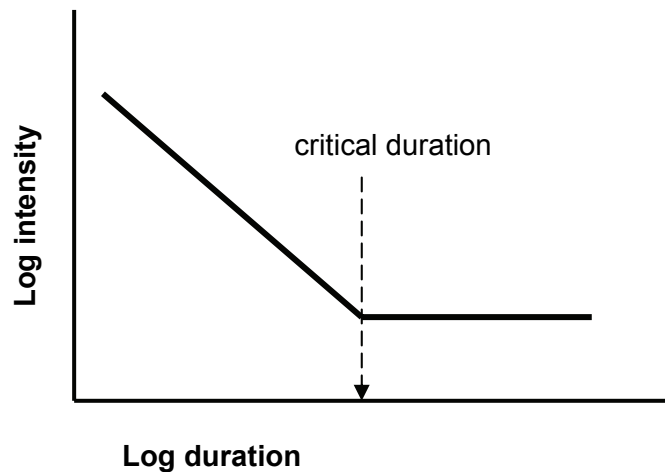


Figure 7-23. Schematic diagram of Bloch's Law, also known as time-intensity reciprocity.

The critical duration is generally between 40 to 100 milliseconds, but it depends on retinal adaptation level, location in the visual field, and color. For instance, the critical duration increases for under scotopic (dark) conditions, for small stimuli, or for single wavelength or narrow-band stimuli.

Critical flicker fusion frequency (CFF)

The CFF is particularly important to display technology, where the refresh rate must exceed the CFF in order to avoid the perception of flicker, which can be annoying. Refresh rate is not the only factor that influences CFF, however. The brightness, color, location in the visual field, and size of the stimulus, as well as variability of the individual, also play a role.

CFF increases as the stimuli becomes brighter; a brighter display would therefore, require a faster refresh rate to avoid the perception of flicker. Based on the same principle, someone who can detect and is annoyed by the flicker of a bright display can eliminate the flicker by reducing the brightness. This phenomenon is described by the Ferry-Porter law, which states that the CFF increases linearly with the log of the luminance. The Ferry-Porter law holds for stimuli of different wavelengths, visual field location and size; although the slopes vary, as described below.

Since the CFF depends on processing speed of the retinal photoreceptor (e.g. faster photoreceptors can perceive flicker at higher frequencies), the type of receptor will influence the CFF. For colored stimuli, the three receptors are the S, M and L cones, which have respective peak sensitivities in the blue, green and red wavelength ranges. When the CFF is measured for these three wavelengths, the slope of the Ferry-Porter function is steepest for the middle-wavelength stimuli, indicating that the M cones are the fastest processors and are more sensitive to flicker with increasing luminance. The function is shallowest for the short-wavelength stimuli, indicating the S cones are slowest and least sensitive to flicker.

The peripheral retina is more sensitive to flicker than the central retina. This can be observed by noting that the flicker of a fluorescent light is more noticeable when viewed with peripheral vision rather straight on. The mid-peripheral retina is the most sensitive to flicker and beyond about 60° from fixation, flicker sensitivity declines.

The Granit-Harper law states that the CFF increases linearly with the log of stimulus area. This applies for retinal eccentricities out to 10° and stimulus sizes up to 50°. Some of this relationship is driven not so much by stimulus size, but by the most temporally-sensitive portion of the retina within the stimulus. For instance, any stimulus that falls even partly on the more sensitive mid-peripheral retina will result in an increased CFF.

Temporal Contrast Sensitivity

Similar to spatial contrast sensitivity, the visual system is variably sensitive to flicker at different frequencies and amplitudes. At lower temporal frequencies (slower on/off), the visual system is fairly consistently sensitive to flicker across a wide range of retinal adaptation levels. As the flicker frequency increases, the visual system becomes more sensitive up to a peak frequency, which under normal photopic levels is around 15 to 20 cycles per second. Figure 7-24 shows how the sensitivity varies as a function of temporal frequency, that is, flicker rate. Beyond the peak frequency, sensitivity declines, and the point where the function intersects the x-axis is the high-contrast temporal resolution limit.

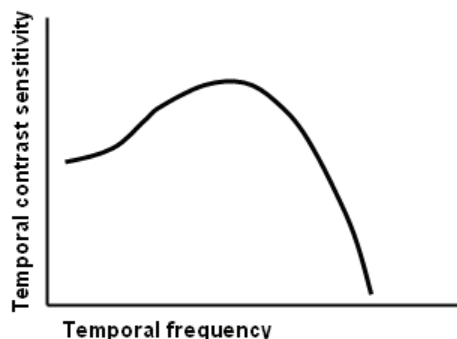


Figure 7-24. Schematic diagram showing how temporal contrast sensitivity varies as a function of temporal frequency.

Eye Movements

A complex system of nerves and muscles work together to coordinate binocular eye movements, with the overall goal to keep the fovea of each eye aimed at the object of regard. The six extraocular muscles (Figure 7-25) are controlled by three cranial nerves (III, IV and VI) and as three agonist/antagonist pairs they serve to move the eyes horizontally (lateral and medial rectus muscles), vertically (superior and inferior rectus muscles), and torsionally (superior and inferior oblique muscles). Two intraocular muscles (iris sphincter and ciliary muscle) are controlled by the oculomotor nerve (III) and serve to manage pupil size and accommodative state. The iris dilator muscle is stimulated by sympathetic neurons in the long ciliary nerves (Netter, 1975).

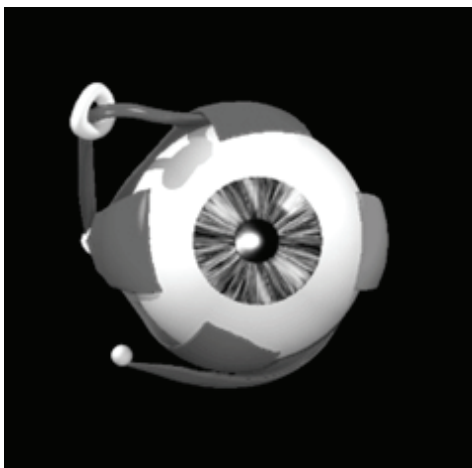


Figure 7-25. Front view of the left eye showing the six extraocular muscles that move the eyeball (Courtesy of Dr. Jason Ellen).

Conjugate eye movements

In conjugate eye movements or *versions*, the eyes move in the same direction. These movements are used for tracking an object that is moving across the visual field (pursuits) or to move quickly towards an object in another part of the visual field (*saccades*). Under the slower pursuit movements, the velocity of the eye is approximately 20° to 50° per second, whereas under faster saccades the velocity of the eye is between 300° to 700° per second. It is important to note that during saccades visual input is momentarily suppressed. This *saccadic suppression* minimizes visual distortion that would occur due to images that rapidly move across the retina. Saccades can either be voluntary, where individuals move their eyes to an object of interest, or involuntary, where the individuals move their eyes in response to an external stimulus, which could be visual, auditory or sensory (pain).

The slow conjugate eye movements include smooth pursuits and the vestibular-ocular reflex (VOR). As previously noted, smooth pursuits are designed to stabilize the image of a moving target on the retina. If the target speed exceeds 50° per second the eyes will start to combine saccades with small intervals of pursuits in order to maintain fixation. This can be demonstrated by moving an object from left to right across the visual field; when the object moves slowly, the eyes follow without saccades, however as speed increases, the eyes are less able to maintain fixation using only smooth pursuits. The VOR helps to keep the eyes on target when the head moves. As the head is rotated, the semi-circular canals in the vestibular system are stimulated, and the information is transmitted to the oculomotor system, which allows the eyes to maintain fixation on the object of regard.

Vergence eye movements

In vergence eye movements, the eyes move in opposite directions; both eyes move towards the midline during *convergence* and away from the midline during divergence. Just as in conjugate eye movements, the primary purpose of vergence eye movements is to keep the foveas of both eyes fixated on the object of regard. As objects come closer to the eyes, the visual axes of the eyes must converge. To accomplish this, the medial rectus muscles of both eyes are engaged. As objects move further away, the opposite occurs; the visual axes diverge due to the action of the lateral rectus muscles of both eyes.

Binocular Vision

Two eyes provide certain advantages over vision with just one eye. For most visual functions such as visual acuity, contrast sensitivity, and extent of the visual field, binocular vision enhances monocular vision. The most significant benefit of binocular vision is stereopsis, which is the powerful perception of depth that is based on the fact that the two eyes view objects from slightly different positions. There are some disadvantages to binocular vision compared to monocular vision. It requires more complex control and processing and thereby renders the person susceptible to problems when the system fails. For example, if the eyes do not align properly the patient may experience double vision and confusion, problems that normally cannot exist in monocular vision. Other binocular problems can lead to eyestrain, fatigue or headaches (Benjamin, 2006; Steinman, Steinman and Garzia, 2000; Tychsen, 1992).

Binocular fusion and alternatives to fusion

Each eye receives an image that is relayed to the brain. The brain combines the two images into one, a process known as binocular fusion. Binocular fusion may be divided into two stages: motor fusion and sensory fusion. Motor fusion refers to the action of the extraocular muscles that rotate the eyes to keep them fixated on the object of regard. Complex neurological mechanisms use control and feedback to coordinate the actions of the twelve extraocular muscles (six for each eye) and point each eye in the correct direction. Assuming good optics, if the eyes are looking at the same object, the two retinal images will be nearly identical. This is a prerequisite for

sensory fusion, which is the neurological process by which the brain combines the two images into one. With defective motor fusion the eyes will not look at the same object and the brain will be faced with a sensory dilemma—how to fuse dissimilar images. If the brain attempts fusion despite the differences, the person will experience visual confusion and diplopia (double vision). Confusion occurs because two different objects will appear in the same location, and diplopia occurs because the object will appear in two non-overlapping positions. This causes visual discomfort and stress, so the brain usually responds automatically to resolve the visual crisis. One solution is to switch attention back and forth between the two images, a condition known as binocular rivalry, but if this condition continues for long, the brain will probably begin to give preference to one image and ignore the other (suppression) (Kimchi et al., 1993). This resolves the sensory dilemma but the person will no longer enjoy binocular vision and its unique benefits.

Stereopsis

Since the two eyes see the world from slightly different vantage points, the right and left retinal images are not exactly identical. In addition the location of objects seen by each eye is slightly different. The differences in visual directions will more pronounced the closer the objects are. If the differences between the right and left eye images are not too great, the visual system is capable of fusing the images. In fact, the visual system detects and analyzes small disparities between the two images to generate the sense of depth perception known stereopsis. Stereopsis allows amazingly fine depth perception, but primarily for objects closer than about 20 feet. For distant objects, differences between the right and left images become insignificant, and stereopsis makes little contribution to depth perception. Instead, we rely on monocular depth cues such as the relative sizes of objects, interposition, convergence of parallel lines, shadows and lighting to provide us with depth perception for faraway objects.

At a typical reading distance of 40 cm, using stereopsis, you should be able to detect that one object is nearer than another if they are separated by a mere 0.5 mm. However, when looking at an object 1000 m away, the minimum separation required for stereopsis is about 750 m. In fact, beyond about 300 meters stereopsis is essentially useless, and we depend primarily on monocular depth cues to judge distances. If the effective separation between the eyes can be increased, image disparities will increase, and there will be a greater stimulus for stereopsis. As an example, field binoculars or large ship-mounted binoculars increase the separation between the viewing positions of the eyes, thereby providing for hyperstereopsis; that is enhanced stereoscopic depth perception. Some helmet-mounted visual systems create the same effect because each eye's telescope is mounted on the outside of the helmet.

Other differences in the images seen by the two eyes can affect binocular vision depending on the degree of the difference. For example, the quality of binocular vision is not significantly affected by small amounts of monocular blur, but large amounts of blur will degrade binocular visual acuity and stereopsis. It may also lead to eyestrain, rivalry and suppression of the blurred eye. Small image size differences between the two eyes can be tolerated, but they may lead to distorted space perception. Sensory fusion will be difficult for size difference greater than 10%, and will probably lead to diplopia, rivalry or suppression. Differences in the brightness of the retinal images can also affect binocularly perceived brightness. This can also cause an erroneous perception of depth for moving objects, an effect known as the Pulfrich phenomenon. This is sometimes demonstrated by having a person binocularly view a pendulum that is swinging in a plane parallel to the forehead. If a tinted lens is placed over the right eye, the pendulum will appear to swing inward, toward the observer when it moves from left to right, and away from the observer when it swings back.

Ocular dominance

Even if the brain receives equal input from the two eyes, one eye is usually preferred as the dominant eye. The dominant eye is sometimes defined as the eye that is used for sighting or aligning objects under binocular conditions, but there are other definitions for ocular dominance. For example, the eye with the more substantial

seeming image, or the eye that is more sensitive to optical blur. The degree to which one eye is dominant over the other varies from person to person, and the dominant eye can switch depending on viewing distance or visual task. In many cases hand and eye dominance are on the same side, but occasionally they are opposite, a condition known as crossed dominance, which can lead to problems in weapons use.

In summary, binocular vision provides enhanced vision compared to monocular vision, and for short distances stereopsis provides extremely precise depth perception.

Conclusion

The eye can be thought of as an optical instrument, but vision depends on much more than optics. Complex physiological processes, including neural image processing are required to perceive an image. The ability to see is further complicated because the visual scene may extend across a wide angular field, objects can be located at different distances, they may be in motion and lighting conditions can vary drastically. Color perception and the addition of a second eye significantly complicate the visual process. By understanding the optics and physiology of vision, engineers and scientists can better design systems that do not interfere with, but rather enhance, vision.

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